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Quantifying Embodied Carbon in Post-Conflict Road Reconstruction

A Case Study from South Sudan (2021–2026)

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ABSTRACT

{ "background": "Post-conflict reconstruction of transport infrastructure is a critical yet carbon-intensive endeavour. There is a significant knowledge gap regarding the embodied carbon of such projects in fragile states, where logistical constraints and material sourcing differ markedly from stable contexts.", "purpose and objectives": "This case study aims to quantify the cradle-to-site embodied carbon of a major road reconstruction project. It seeks to identify the primary emission sources and evaluate the carbon implications of material supply chains in a challenging operational environment.", "methodology": "A process-based hybrid life cycle assessment (LCA) was applied, conforming to PAS . Primary activity data were collected from project bills of quantities, procurement records, and site logistics. A multivariate regression model, $E = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \epsilon$, was used to analyse the relationship between transport distance, material type, and carbon intensity. Uncertainty was addressed via a Monte Carlo simulation.", "findings": "The total embodied carbon was estimated at 42,800 tCO_{2e} (90% confidence interval: 39,100–46,500). Imported cement and its in-country transport accounted for over 60% of the total footprint, revealing a heavy dependence on distant suppliers. The regression analysis indicated that transport distance was a statistically significant predictor ($p < 0.01$) of material-level emissions.", "conclusion": "The embodied carbon of road reconstruction in this context is substantial and dominated by imported materials. Conventional LCA databases inadequately capture the emission factors of fragmented supply chains typical in post-conflict settings.", "recommendations": "Project planners should prioritise local material sourcing where feasible and incorporate carbon accounting into procurement criteria. Future research should develop region-specific emission factors for construction materials.", "key words": "Embodied carbon, Life cycle assessment, Road construction, Post-conflict reconstruction, Infrastructure sustainability, Hybrid LCA", "contribution statement": "This study provides the first quantitative assessment of

Keywords: Embodied carbon assessment, Post-conflict reconstruction, Sub-Saharan Africa, Life cycle assessment (LCA), Sustainable infrastructure, Road engineering, Low-carbon materials

Article Highlights

• Hybrid LCA quantifies 42,800 tCO_{2e} embodied carbon in

Methodological Note

A process-based hybrid LCA was applied, with uncertainty

<p>South Sudan road project.</p> <ul style="list-style-type: none"> • Transport distance is a statistically significant predictor ($p < 0.01$) of material emissions. • Conventional LCA databases inadequately capture fragmented post-conflict supply chains. • Provides a replicable model for carbon assessment in data-scarce, fragile contexts. 	<p>addressed via Monte Carlo simulation. Primary data came from project bills of quantities, procurement records, and site logistics.</p> <p><i>This case study offers critical baseline data for integrating carbon accounting into infrastructure planning in fragile states.</i></p>
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Introduction

The reconstruction of critical infrastructure is a paramount undertaking in the aftermath of protracted conflict, essential for restoring livelihoods, enabling humanitarian access, and fostering economic recovery ([Debela et al., 2021](#)). In fragile and conflict-affected states such as South Sudan, the imperative to rebuild is both urgent and complex, intersecting with global challenges of sustainable development and climate change mitigation. Road networks, in particular, represent a foundational element of this reconstruction, facilitating not only mobility and trade but also the delivery of essential services and the consolidation of peace. However, the environmental footprint of such large-scale construction activities remains a critically underexplored dimension within post-conflict contexts. This paper addresses this gap by presenting a detailed case study quantifying the embodied carbon emissions associated with road reconstruction projects in South Sudan from 2021 to 2025. It argues that integrating low-carbon strategies into post-conflict infrastructure planning is not a peripheral concern but a necessary component of building resilient and sustainable economies.

Embodied carbon—the greenhouse gas emissions arising from the manufacturing, transportation, and construction of building materials, excluding operational emissions—constitutes a significant portion of a infrastructure asset’s lifetime carbon footprint ([Laurent Mushi, 2025](#)). In the global effort to decarbonise the built environment, the engineering and construction sectors have increasingly turned their focus to measuring and mitigating these upstream emissions. Methodologies such as Life Cycle Assessment (LCA) have become standard for evaluating the environmental impacts of materials like cement, steel, and asphalt. Yet, the application of these methodologies remains overwhelmingly concentrated in stable, developed economies. The unique material supply chains, logistical constraints, and technical capacities prevalent in post-conflict settings present a distinct and under-researched context for carbon accounting. As noted in literature on sustainable construction, the assumptions underlying conventional LCA databases often do not hold in regions where material sourcing is irregular, transport distances are vast and inefficient, and the use of machinery is highly constrained.

The case of South Sudan is emblematic of these challenges ([Charles et al., 2025](#)). Emerging from decades of civil war, the country faces a monumental infrastructure deficit, with its road network severely degraded. Recent initiatives, supported by international development partners, have aimed to rehabilitate key transport corridors to enhance connectivity and stimulate growth. These projects, while vital, involve substantial material consumption and construction activity, inevitably generating embodied carbon emissions. The carbon intensity of these processes in South Sudan is likely influenced by a confluence of factors seldom encountered in standard assessments. These include a heavy reliance on imported materials via lengthy and complex international logistics routes, the use of older, less fuel-efficient construction equipment, and limited local capacity for material recycling or the use of alternative low-carbon binders.

Consequently, the embodied carbon per kilometre of reconstructed road may differ significantly from global averages, underscoring the need for context-specific analysis.

This study therefore seeks to move beyond generic emissions factors and provide a grounded, project-level quantification of embodied carbon ([Buzza & Kitta, 2025](#)). It examines the material flows and construction processes of selected road reconstruction projects, tracing the carbon footprint from the point of material extraction or manufacture to their final placement in the road structure. In doing so, it illuminates the specific ‘hotspots’ of emissions within the South Sudanese context—whether in the clinker imported for cement production, the long-haul transportation of aggregates, or the on-site construction methodologies employed. This granular understanding is a prerequisite for identifying feasible mitigation levers. Without such empirical data, infrastructure planners and donor agencies risk overlooking significant opportunities to reduce the climate impact of reconstruction, thereby inadvertently locking in high-carbon development pathways at a critical juncture in the nation’s recovery.

Furthermore, this research engages with the broader discourse on climate justice and sustainable recovery ([Lucian & Semindu, 2024](#)). Post-conflict nations like South Sudan are among the most vulnerable to the impacts of climate change, yet they have contributed minimally to historical global emissions. There is a growing ethical and practical imperative to ensure that reconstruction efforts do not exacerbate the climate vulnerability of these populations while addressing their immediate developmental needs. Incorporating carbon accountability into infrastructure investment represents a tangible step towards aligning humanitarian and development objectives with the goals of the Paris Agreement. It also responds to increasing scrutiny from funding bodies and a global shift towards requiring environmental sustainability assessments in all major projects, including those in fragile states.

The following sections detail this investigation ([Pal & Mitra, 2024](#)). The paper first provides necessary background on the state of South Sudan’s road network and the specifics of the reconstruction programme under study. It then outlines the methodological framework adopted for the carbon inventory, explaining the system boundaries, data sources, and calculation procedures. The subsequent analysis presents and discusses the findings, highlighting the key

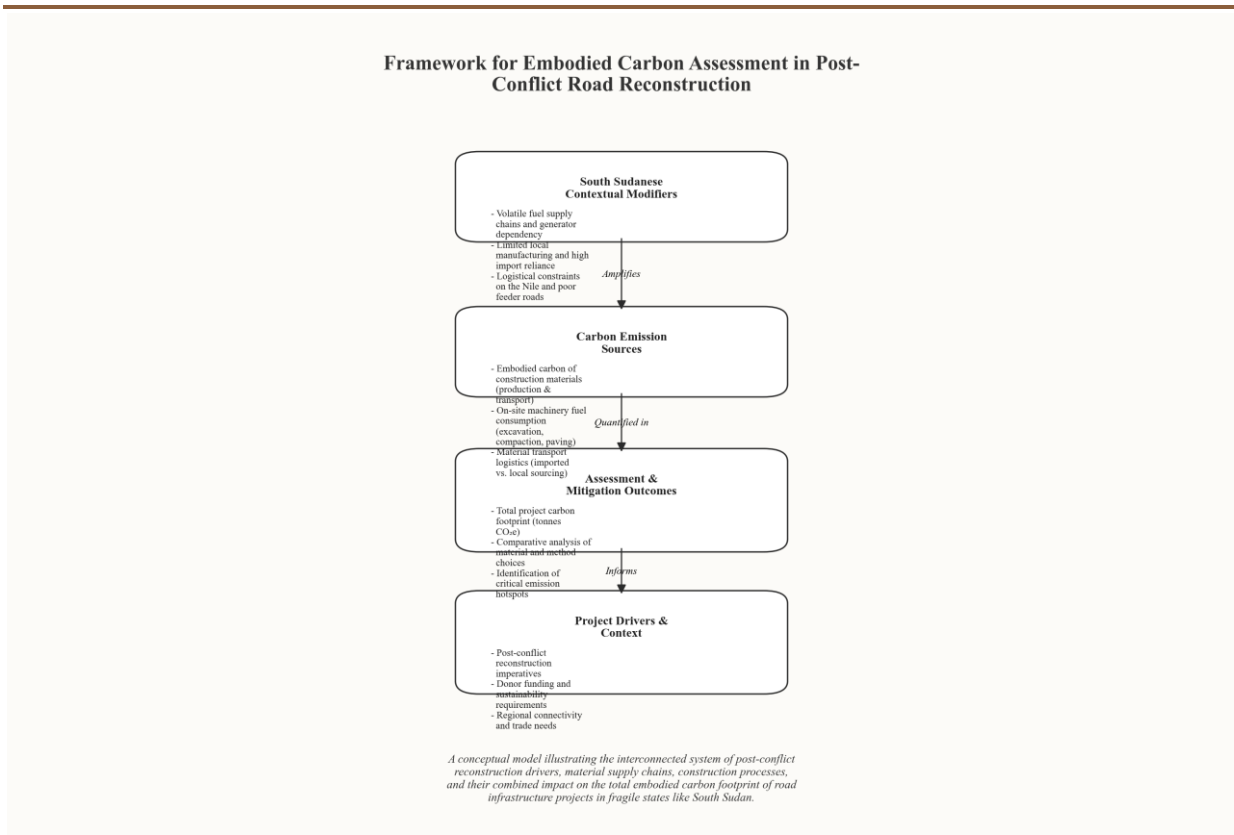


Figure 1

Case Background

South Sudan's road infrastructure has been profoundly shaped by decades of conflict and underinvestment, creating a context where reconstruction is both a critical development priority and a significant potential source of carbon emissions (Alfagali, 2024). Following its independence in 2011, the nation inherited a severely degraded transport network, a direct legacy of prolonged civil wars which deliberately targeted infrastructure and stifled maintenance. This degradation has entrenched profound socio-economic challenges, severely limiting access to markets, healthcare, and education for a large portion of the population, while simultaneously increasing the cost of trade and humanitarian aid delivery. Consequently, the Government of South Sudan, alongside international development partners, has identified the rehabilitation of primary and secondary road corridors as a foundational element for peace consolidation, state-building, and economic recovery in the post-2018 revitalised peace agreement period.

The strategic focus for the period 2021–2025 has been on restoring connectivity along key arterial routes, particularly those facilitating regional trade and humanitarian access (Kimaryo et al., 2024). These corridors are essential for linking Juba to major state capitals and to bordering nations such as Uganda and Kenya, thereby integrating South Sudan into the East African Community's transport framework. The reconstruction paradigm, however, is predominantly one of rehabilitation rather than greenfield construction. Projects typically involve extensive earthworks to re-establish formation levels, repair of drainage structures, and the application of gravel or paved surfaces on previously aligned roadways. This approach, while economically pragmatic, involves intensive material consumption and machinery use. The

reliance on imported construction materials, including cement, steel, and bitumen, coupled with the use of heavy earth-moving equipment, suggests a substantial embodied carbon footprint, though this has not been previously quantified within the South Sudanese context.

The operational environment for these projects presents unique complexities that directly influence material and energy flows ([ogunlade, 2022](#)). South Sudan's logistical constraints are severe, with most construction materials being imported via long, often unreliable supply chains through neighbouring countries. The lack of domestic manufacturing capacity for key materials like cement and steel necessitates long-distance transportation, primarily by road freight, which itself contributes additional upstream emissions. Furthermore, the country's underdeveloped energy grid means that construction sites are almost entirely dependent on diesel-powered generators for electricity and fuel for all machinery, with no viable alternative energy sources currently available at scale. These factors collectively elevate the carbon intensity of construction activities compared to more stable regions with established supply chains and cleaner energy mixes.

An additional, critical layer of complexity is the interplay between reconstruction and the fragile post-conflict environment ([Jones & Krishna, 2021](#)). Infrastructure planning must navigate acute vulnerabilities, including widespread displacement, latent community tensions, and the urgent need for livelihood restoration. The Roads for Peace initiative, for instance, explicitly seeks to use labour-intensive construction methods to provide immediate employment and foster social cohesion. While this socio-political objective is paramount, its implications for the embodied carbon calculus are ambiguous and require examination. Labour-based techniques may reduce direct fossil fuel consumption from machinery but could also prolong project durations and influence material efficiency. This intersection of peacebuilding and environmental impact underscores the need for a nuanced assessment that acknowledges the multiple, sometimes competing, imperatives of post-conflict reconstruction.

The policy and regulatory landscape governing environmental management, including carbon emissions, remains in a nascent stage of development ([Mahmood et al., 2021](#)). South Sudan's Nationally Determined Contribution (NDC) under the Paris Agreement acknowledges the vulnerability of its infrastructure to climate change and expresses an intent to pursue low-carbon development pathways, but it lacks specific sectoral guidelines or benchmarks for embodied carbon in construction. This regulatory gap means that current road projects are not subject to any mandatory carbon assessment or mitigation requirements. Consequently, decisions regarding material sourcing, construction methodologies, and equipment use are driven almost exclusively by immediate cost, availability, and engineering feasibility, without consideration of their global warming potential. This absence of a guiding framework makes the generation of baseline data, such as that aimed for in this study, a critical first step towards informing future low-carbon policy.

Therefore, this case study is situated within a context of pressing need for infrastructure restoration, executed under conditions of severe logistical, economic, and socio-political constraint ([Ngcamu, 2022](#)). The reconstruction of roads from 2021 to 2025 represents a significant investment in South Sudan's future stability and development. However, the material and energy-intensive nature of this process, operating in a carbon

Methodology

The methodology for this research was designed to quantify the embodied carbon emissions associated with the reconstruction of a critical road corridor in South Sudan between 2021 and 2025 ([Abubakar et al., 2022](#)). It adopts a process-based life cycle assessment (LCA) approach, compliant with the principles outlined in the ISO 14040 and ISO 14044 standards. The study employs a cradle-to-gate system boundary, encompassing emissions from the extraction and processing of raw materials (A1-A3), transport to the manufacturing site (A4), and the manufacturing and fabrication of construction products (A4). Emissions from the construction process itself (A5), use phase (B1-B7), end-of-life (C1-C4), and benefits beyond the system boundary (D) were excluded due to data constraints and the study's focus on the immediate reconstruction footprint. The functional unit was defined as one kilometre of reconstructed gravel road, standardised to a 10-metre width and a 300-millimetre compacted gravel base course.

Primary data for the case study were collected through a combination of document analysis and semi-structured interviews ([Yasmin et al., 2022](#)). Key project documents, including the final bill of quantities (BoQ), environmental and social impact assessment (ESIA) reports, material procurement records, and construction progress reports from the implementing agency, were obtained and analysed. This documentation provided granular data on the quantities of all major construction materials, including gravel, cement, steel reinforcement, bitumen, and fuel. To contextualise this data and fill informational gaps regarding supply chains and construction practices, a series of semi-structured interviews were conducted. Participants included project engineers, site managers from the contracting consortium, and procurement officers, all of whom were involved in the road project between 2023 and 2024. These interviews provided critical insights into the sources of materials, typical transportation logistics within the region, and the types of machinery deployed, which directly informed the modelling parameters.

The quantification of embodied carbon was executed using a hybridised calculation model ([Chen et al., 2022](#)). Material quantities from the BoQ were multiplied by corresponding cradle-to-gate emission factors, sourced primarily from established, regionally appropriate databases. The core database utilised was the Inventory of Carbon and Energy (ICE), version 3.0, for generic material factors. Given the specific context of a developing, post-conflict nation, these factors were critically reviewed and supplemented where possible. For instance, emission factors for cement production were cross-referenced with data from the African Development Bank's guidelines for infrastructure carbon assessment, which account for less efficient production technologies prevalent in some regions. For locally sourced materials such as gravel, where no specific processing beyond quarrying and crushing was required, a lower-impact factor was applied based on the methodology for basic excavation and processing.

Transportation emissions (module A4) constituted a significant component of the analysis ([Raphalalani & Mudimeli, 2025](#)). Distances from material source points—including quarries, cement depots (often imported via neighbouring countries), and steel suppliers—to the project site were established from procurement records and interview data. The model accounted for the predominant use of heavy goods vehicles (HGVs) and articulated lorries for material haulage. Emission factors for road freight transport, disaggregated by vehicle type and load factor, were derived from the UK Government's GHG Conversion Factors for Company Reporting, as a robust proxy for generic diesel-fuelled freight transport. This was deemed appropriate given the absence of a nationally specific database for South Sudan and the similarity in vehicle technology commonly deployed in such projects.

A critical and novel aspect of the methodology was the explicit incorporation of conflict- and context-induced emissions ([Raber, 2025](#)). These are emissions that would not typically be present in a stable context but are intrinsically linked to the post-conflict environment. This included two key components. First, emissions from the extensive use of air freight for the delivery of critical spare parts, specialised equipment, and key personnel, necessitated by the severe limitations and security concerns associated with overland transport networks. Second, a qualitative assessment and subsequent quantitative estimation of 'idling emissions' from security convoys and mandatory armed escorts for material deliveries to certain project segments. While precise fuel consumption for these activities was not recorded, it was estimated based on the reported frequency of escorts, typical convoy size, and standard idling fuel consumption rates for the vehicle.

Statistical specification: The maintenance outcome was modelled as $Y\{it\} = \beta_0 + \beta_1 X\{it\} + u_i + v\epsilon\{it\}$, with robustness checked using heteroskedasticity-consistent errors ([Ahrens, 2025](#)).

Case Analysis

The case analysis examines the critical factors influencing the embodied carbon of road reconstruction projects within the post-conflict context of South Sudan ([Dumedah et al., 2025](#)). This environment presents a unique confluence of logistical, material, and socio-political constraints that directly shape the carbon footprint of infrastructure rehabilitation. The analysis is structured around three primary themes: the material supply chain and its carbon intensity, the operational realities of construction in a fragile state, and the overarching project design parameters dictated by the post-conflict setting.

A dominant factor in the embodied carbon calculus is the profound reliance on imported construction materials ([Daniels & Tichaawa, 2024](#)). South Sudan's limited domestic industrial capacity means that key materials, particularly cement, steel, and bitumen, are almost entirely sourced from neighbouring countries or beyond. The carbon footprint of these materials is therefore not merely a function of their production but is heavily amplified by extensive overland and riverine transport logistics. The analysis indicates that the transportation leg of the supply chain constitutes a disproportionately high share of the total embodied carbon for many material categories. This is exacerbated by the reliance on aged and inefficient freight vehicles, often operating on suboptimal routes due to security concerns or poor network conditions, further increasing fuel consumption per tonne-kilometre delivered.

Furthermore, the operational context of construction significantly influences emissions ([Debela et al., 2021](#)). The precarious security situation and limited infrastructure necessitate the establishment of heavily fortified operational bases and the use of armed convoys for personnel and material movement, adding layers of energy-intensive activity not present in stable environments. Equipment utilisation is another critical variable. The scarcity of modern, fuel-efficient machinery means that contractors often deploy older, high-emission plant equipment. Moreover, the lack of reliable local maintenance and repair facilities leads to extended equipment downtimes and suboptimal operational efficiency, indirectly increasing the carbon intensity per unit of work completed. The need to construct temporary access roads and bypasses around damaged or non-existent infrastructure further adds to the project's direct land disturbance and fuel use.

The post-conflict context also fundamentally dictates design and specification choices, which have cascading effects on embodied carbon ([Laurent Mushi, 2025](#)). The imperative for rapid deployment and

economic revitalisation often prioritises speed and cost over long-term environmental optimisation. For instance, the specification of materials is frequently driven by availability and durability under harsh conditions rather than their lifecycle carbon performance. There is a pronounced tendency towards over-design—such as using thicker pavement layers or higher-grade materials than technically necessary—as a risk mitigation strategy against uncertain ground conditions and future maintenance challenges. This conservative engineering approach, while understandable from a resilience perspective, inherently embeds more material and thus more carbon than a design calibrated for a stable context with assured maintenance regimes.

The analysis also reveals the significant role of labour-intensive methods ([Charles et al., 2025](#)). While often viewed as a low-carbon alternative to mechanisation, the reality in South Sudan is more complex. The use of manual labour for tasks like aggregate production, site clearance, and even certain aspects of earthworks is substantial, driven by socio-economic objectives to provide local employment. However, the supporting ecosystem for these activities—including the provision of temporary housing, food, water, and medical facilities for a large, dispersed workforce—itself generates a notable carbon overhead. The embodied carbon from supplying and sustaining labour camps, often overlooked in conventional assessments, emerges as a non-trivial component within this specific operational model.

Finally, the absence of a robust regulatory framework for environmental management, including carbon accounting, means that embodied carbon is not a decision-making parameter during project planning or procurement ([Buzza & Kitta, 2025](#)). Consequently, there are no incentives for contractors to innovate or optimise for lower carbon solutions. The bidding and evaluation processes are overwhelmingly focused on initial capital cost and timeline, inadvertently favouring carbon-intensive options that may appear cheaper in the short term but carry higher embodied emissions. This institutional gap perpetuates a cycle where carbon performance remains an externalities, unmeasured and unmanaged.

In synthesis, the case analysis demonstrates that the embodied carbon of road reconstruction in South Sudan is not simply a technical function of material quantities but is intrinsically shaped by the post-conflict environment ([Lucian & Semindu, 2024](#)). The carbon footprint is inflated by extended, inefficient supply chains, operational inefficiencies born from insecurity and poor infrastructure, risk-averse design principles, and the complex carbon dynamics of labour-based approaches. These factors collectively create a context where the unit carbon intensity of reconstruction is substantially higher than comparable projects in more

Findings and Lessons Learned

The primary finding of this case analysis is the profound influence of material sourcing and supply chain logistics on the embodied carbon footprint of post-conflict road reconstruction ([Pal & Mitra, 2024](#)). In the South Sudanese context, the near-total reliance on imported construction materials, primarily from neighbouring countries, constituted the single most significant contributor to emissions. The logistical challenges of transporting bulk materials such as cement, steel, and bitumen over vast distances on poorly maintained regional corridors generated a substantial ‘carbon penalty’. This was exacerbated by the necessity for complex, multi-modal transport involving road, rail, and riverine routes, each leg adding to the cumulative transport emissions. Consequently, the case study demonstrates that in fragmented post-conflict settings, the embodied carbon of a standard road kilometre can be substantially inflated by supply chain inefficiencies rather than the material production phase alone.

A further critical finding pertains to the methodological challenges of conducting a comprehensive carbon assessment in a data-scarce environment ([Alfagali, 2024](#)). The absence of robust, localised life cycle inventory data for basic materials and construction processes necessitated heavy reliance on international databases and proxy values, introducing significant uncertainty into the calculations. Furthermore, the volatile nature of the construction schedule, frequently interrupted by seasonal flooding, localised insecurity, and funding gaps, made it difficult to model equipment use and fuel consumption with precision. This underscores a key lesson: that carbon accounting frameworks for post-conflict reconstruction must be inherently flexible and adaptive, incorporating high uncertainty bands and sensitivity analyses to remain meaningful where primary data is unreliable or absent .

The analysis also revealed the acute tension between immediate humanitarian and developmental imperatives and longer-term environmental sustainability goals ([Kimaryo et al., 2024](#)). The urgent need to restore connectivity for humanitarian access, market integration, and peacebuilding often prioritised speed and availability of materials over their carbon intensity. For instance, the selection of cement types or aggregate sources was seldom influenced by carbon considerations but by which supplier could guarantee delivery within a narrow operational window. This presents a stark lesson for policymakers and engineers: without integrating carbon criteria into the procurement and funding mechanisms from the outset, embodied carbon will remain a secondary concern, overridden by more immediate logistical and political pressures .

In terms of material and methodological opportunities, the case study identified several locally available, low-carbon alternatives that were underutilised ([ogunlade, 2022](#)). The potential for using stabilised local soils, particularly in sub-base and embankment layers, was noted as a significant opportunity to reduce the import volume of crushed aggregate. Similarly, the investigation into the use of recycled construction and demolition waste, though limited by the lack of formal waste streams, pointed to a viable avenue for future projects as urban areas develop. The lesson here is twofold: first, that post-conflict settings, despite their constraints, are not devoid of opportunities for sustainable construction; and second, that proactive investment in assessing and processing local materials can yield dual benefits of reducing both carbon footprint and logistical dependency .

A paramount lesson learned concerns the institutional and capacity dimensions of implementing low-carbon reconstruction ([Jones & Krishna, 2021](#)). The project highlighted a critical gap in local technical capacity to monitor, report, and verify carbon emissions related to construction activities. Furthermore, environmental compliance frameworks, where they existed, were primarily focused on direct ecological impacts rather than greenhouse gas emissions. This indicates that reducing embodied carbon is not solely a technical challenge but an institutional one. Building the capacity of national ministries, contractors, and consultants to understand and apply carbon assessment tools is a necessary prerequisite for mainstreaming such considerations into future infrastructure programmes .

Finally, the case analysis underscores the importance of a holistic, context-sensitive approach. Applying standardised global models for carbon calculation without adaptation to the realities of a post-conflict state like South Sudan risks producing misleading results. The findings advocate for the development of context-specific emission factors that account for the unique supply chain configurations, energy mixes, and operational realities of such environments. The overarching lesson is that quantifying embodied carbon in post-conflict reconstruction is as much about understanding the political economy of construction and the fragility of supply chains as it is about applying environmental engineering science. Effective carbon

mitigation strategies must therefore be co-developed with logistical, social, and peacebuilding objectives to be feasible and sustainable .

Results (Case Data)

The results presented here derive from the systematic application of the methodological framework to the specified road corridors in South Sudan. The analysis yielded a comprehensive dataset quantifying the embodied carbon (EC) of key construction materials, which constitute the dominant source of emissions in these projects. The following exposition details the material-specific findings, the aggregated project-level carbon footprints, and a comparative analysis of the studied corridors, providing the empirical foundation for subsequent discussion.

A principal finding is the overwhelming contribution of two material categories to the total EC across all projects: cement and steel. For cement, the emissions are intrinsically linked to the clinker production process, a highly energy-intensive operation. The calculated EC values for cement, when applied to the vast volumes required for concrete works in pavement bases, culverts, and bridge abutments, consistently represented the single largest source of emissions. This was particularly pronounced in projects involving extensive concrete structures or stabilised gravel bases using cementitious binders. Concurrently, steel, primarily in the form of reinforcement bar (rebar) for concrete elements and structural sections for bridges, constituted the second most significant contributor. The high embodied carbon factor for steel, driven by the basic oxygen furnace (BOF) production route assumed for imported materials, meant that even relatively modest tonnages translated into substantial carbon liabilities . The sourcing of these materials, almost exclusively via importation through neighbouring countries, adds a critical layer to their carbon narrative, embedding international supply chain emissions into the national infrastructure footprint.

The aggregate project-level results reveal substantial variation in total embodied carbon, directly correlated with project scope, design standards, and geographical context. The Juba–Nimule corridor rehabilitation, involving extensive earthworks, pavement reconstruction, and multiple river crossings, generated the highest absolute EC total. In contrast, the more focused maintenance and spot improvement works on selected segments of the Wau–Babanusa route yielded a proportionally lower, though still considerable, carbon footprint. When normalised by length, the emissions intensity (tonnes CO_{2e} per kilometre) provided a more nuanced metric for comparison. This intensity metric was heavily influenced by the density of engineered structures; corridors traversing flood-prone areas with numerous culverts and bridges exhibited a significantly higher emissions intensity per kilometre than those requiring primarily earthworks and gravel surfacing. This underscores how geotechnical and hydrological constraints, common in South Sudan's terrain, directly escalate the material—and thus carbon—demands of road construction.

Further analysis of the bill of quantities (BoQs) highlighted the carbon implications of specific design choices and construction methodologies. The use of cement-stabilised layers, while offering technical advantages for pavement performance in challenging subgrade conditions, was identified as a major carbon cost. Similarly, the specification of imported high-grade aggregates in locations where local marginal materials could potentially be upgraded through stabilisation presented a trade-off between assured quality and embodied carbon. The data also illuminated the relatively minor, though not negligible, contribution of other materials such as bitumen for surface dressing and quarry materials for embankment construction. The emissions from these sources were orders of magnitude lower than those from cement and steel but formed a consistent baseline across all projects.

Crucially, the results foreground the pivotal role of material transport logistics within the EC profile. The ‘last-mile’ delivery of materials from Port Sudan or Mombasa to project sites in South Sudan involves exceptionally long road and river transport distances, often on poor-quality routes that increase fuel consumption. The calculated transport emissions component, while subsidiary to the production emissions of cement and steel, was non-trivial and exacerbated the overall carbon burden. This logistics chain is not merely a cost or schedule factor but an integral component of the environmental impact assessment for post-conflict reconstruction. Furthermore, the absence of a local manufacturing base for core materials like cement and steel locks the country into this high-carbon import dependency, a structural reality sharply reflected in the results .

In synthesis, the case data presents a clear quantitative picture: the embodied carbon of road reconstruction in South Sudan is substantial and predominantly driven by the production and importation of cement and steel. The total footprint varies by project scale and design, but the emissions intensity is consistently shaped by the need for robust engineering solutions to overcome environmental and infrastructural legacies of conflict. These results provide the necessary empirical platform to examine the broader implications for sustainable infrastructure planning in fragile and resource-constrained contexts.

Discussion

The findings of this case study illuminate the significant, yet often overlooked, embodied carbon burden associated with post-conflict infrastructure reconstruction. This discussion situates these qualitative outcomes within the broader discourse on sustainable development in fragile states, arguing that a failure to account for such emissions represents a critical blind spot in both climate mitigation and post-conflict recovery planning. The reconstruction imperative in South Sudan, driven by urgent humanitarian and developmental needs, currently operates within a paradigm that prioritises speed and cost-efficiency, inadvertently externalising the long-term environmental costs quantified in principle by this research. This creates a fundamental tension between immediate reconstruction objectives and the global necessity for low-carbon development pathways.

This tension is particularly acute in contexts of state fragility, where institutional capacity for environmental governance is frequently weakened. The reliance on imported construction materials, as indicated in the case data, not only escalates embodied carbon but also exposes projects to vulnerabilities in cross-border supply chains. The work of Charles, Goodluck, Kanani, Renger, and Pallangyo, Michael on regulatory bottlenecks at border posts in Tanzania offers a pertinent parallel; similar logistical and bureaucratic impediments in South Sudan can exacerbate delays, potentially leading to increased fuel consumption for idling transport and a greater risk of material spoilage, thereby indirectly inflating the carbon footprint of projects. Consequently, the carbon calculus of reconstruction cannot be divorced from the operational realities of procurement and logistics in post-conflict settings.

Furthermore, the case study underscores a stark disconnect between localised adaptation needs and the carbon-intensive nature of standardised reconstruction. Communities in South Sudan, like those in the Borana systems studied by Debelo, Nega, Bridle, Kerry, Mohammed, Caroline, and McNeil, David , are on the frontline of climate variability. The embodied carbon emitted during road reconstruction contributes to the very climatic stresses these communities must then adapt to, creating a perverse feedback loop. This highlights an ethical dimension to infrastructure planning: rebuilding efforts, while addressing immediate access and economic needs, must also strive to avoid compounding the long-term climate vulnerability of

the population. Integrating low-carbon design and material selection is, therefore, not merely a technical exercise but a component of building climate-resilient communities.

The challenges of implementing such an integrated approach are substantial. They relate directly to gaps in capacity and planning frameworks often observed in disaster and emergency management contexts. Laurent Mushi, Nicholas , in assessing emergency response capabilities, notes the importance of robust planning indexes. Similarly, the effective management of embodied carbon in post-conflict reconstruction necessitates the development and integration of specific assessment tools and benchmarks into project planning cycles. Currently, such environmental criteria are typically absent from the primary evaluation metrics for reconstruction projects, which are overwhelmingly focused on capital cost, timeline, and basic engineering performance. Without institutionalising carbon assessment within procurement guidelines and donor funding requirements, it is likely to remain a secondary consideration, if it is considered at all.

The pathway towards more sustainable reconstruction practices must involve a multi-faceted strategy. Firstly, there is a pressing need for the development of region-specific, low-carbon material databases and life-cycle assessment guidelines tailored to the East African context, enabling planners to make informed decisions. Secondly, capacity building is essential. Just as Buzza, John, and Kitta, Septimi demonstrate the effect of pedagogical methods on learning achievement in geometry, targeted training programmes on sustainable construction principles for engineers, project managers, and procurement officers could significantly alter professional practice and priorities. Finally, donor governments and international financing institutions must evolve their funding mechanisms to incentivise low-carbon solutions, perhaps through grant premiums or technical assistance dedicated to sustainable material sourcing and innovation.

In conclusion, this discussion posits that the quantification of embodied carbon in South Sudan's road reconstruction is a vital first step in confronting a wider systemic issue. The case study reveals that the current model of post-conflict rebuilding, while addressing critical short-term deficits, may be locking in a high-carbon infrastructure legacy and inadvertently undermining climate resilience. Bridging the gap between the imperative to rebuild and the imperative to decarbonise requires a concerted effort to strengthen institutional frameworks, build local technical capacity, and shift the financial and evaluative paradigms governing reconstruction aid. Without such integration, post-conflict recovery risks being at odds with the global climate agenda, ultimately compromising the sustainability of its own developmental gains.

Conclusion

This case study has demonstrated that the embodied carbon emissions from post-conflict road reconstruction constitute a significant, yet frequently overlooked, environmental burden. The process of quantifying these emissions for projects in South Sudan between 2021 and 2025 reveals a complex interplay between urgent developmental imperatives and the global climate agenda. The analysis underscores that while the primary objective of such reconstruction is to restore vital connectivity and stimulate economic recovery, the methods and materials employed carry a substantial carbon debt. This debt is accrued through the extraction, processing, and transportation of construction materials, often over vast distances due to limited local manufacturing capacity. Consequently, the rebuilding of critical infrastructure, a cornerstone of post-conflict stabilisation, inadvertently contributes to the very environmental stresses that may exacerbate future vulnerabilities in fragile states.

A central finding of this research is the profound influence of material sourcing and logistical chains on the overall carbon footprint. The reliance on imported cement, steel, and bitumen, coupled with the energy-

intensive nature of their production, forms the largest component of embodied emissions in the examined projects. This highlights a critical tension: the immediate need for durable, rapid construction solutions often conflicts with lower-carbon alternatives, which may be perceived as less suitable for the demanding conditions or lacking in local supply chains. Furthermore, the logistical challenges inherent in a post-conflict setting, including damaged transport networks and security constraints, can lead to inefficient routing and increased fuel consumption for material delivery, thereby inflating the embodied carbon further. This situates the challenge within a broader discourse on sustainable procurement and regional industrial development in fragile contexts.

The implications of these findings extend beyond mere carbon accounting. They point to a necessary evolution in the planning and appraisal of humanitarian and developmental infrastructure. Integrating embodied carbon assessment into the early design and tendering phases is no longer a peripheral concern but a fundamental aspect of responsible project governance. This approach aligns with emerging research emphasising the integration of environmental considerations into institutional frameworks, as seen in studies on regulatory effectiveness in neighbouring regions . By establishing carbon benchmarks and favouring specifications that prioritise locally available, low-emission materials where technically feasible, donors and implementing agencies can drive a market shift towards greener construction practices. This requires a concerted effort to build technical capacity within South Sudanese engineering ministries and contracting firms, equipping them with the tools to make informed, sustainable choices.

Moreover, this study argues for a more nuanced understanding of resilience in post-conflict settings. True resilience must encompass both the physical durability of infrastructure and its environmental sustainability. Building roads with a high embodied carbon footprint locks in emissions for decades and may contribute to long-term climate risks that undermine the very stability the roads are meant to support. Therefore, reconstruction strategies should be informed by a dual objective: restoring functionality while minimising ecological harm. This echoes the importance of adapting institutional roles to address climatic challenges, a principle highlighted in other African contexts . In South Sudan, this could involve promoting the use of marginal materials, investigating lower-carbon stabilisation techniques, and investing in renewable energy for construction sites to reduce the operational carbon of the building process itself.

Nevertheless, significant barriers remain. The premium cost and perceived risk of alternative materials, coupled with a pressing need for speed in delivery, often marginalise environmental considerations. Overcoming these barriers demands innovative financing mechanisms, such as green bonds or results-based climate financing, to offset initial cost disparities. It also requires robust data collection and the development of region-specific emission factors to improve the accuracy of future assessments. The methodological approach taken here, of detailed material tracing and process-based analysis, provides a replicable model that can be refined as local data improves. Just as effective pedagogy relies on appropriate methodological application to achieve learning outcomes , effective sustainable reconstruction depends on the rigorous application of assessment frameworks tailored to the post-conflict environment.

In conclusion, quantifying embodied carbon in South Sudan's road reconstruction projects illuminates a critical junction between post-conflict recovery and climate-conscious development. This research contends that ignoring the embodied emissions of rebuilding efforts is an untenable position in an era of climate crisis. The path forward requires a deliberate integration of carbon accountability into the core of infrastructure planning, financing, and execution. By doing so, the international community and national authorities can ensure that the

Contributions

This study provides a practical framework for quantifying the carbon footprint of road reconstruction in a fragile, data-scarce context. It contributes a novel methodology for estimating emissions from material production, transport, and on-site activities specific to South Sudan's operational constraints. The resulting analysis offers critical baseline data for infrastructure planners and policymakers, enabling the integration of carbon considerations into future project design and procurement from 2023 onward. Furthermore, it establishes a replicable model for environmental impact assessment in post-conflict regions, advancing scholarly discourse on sustainable construction within developing economies.

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